Nuclear Inst. and Methods in Physics Research, A 879 (2018) 134–140

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Geant4 simulations of the absorption of photons in CsI and NaI produced by electrons with energies up to 4 MeV and their application to precision measurements of the β-energy spectrum with a calorimetric technique

X. Huyan [a,b], O. Naviliat-Cuncic [a,b,*], P. Voytas [c], S. Chandavar [a], M. Hughes [a,b], K. Minamisono [a,b], S.V. Paulauskas [a]

[a] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI, USA
[b] Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA
[c] Department of Physics, Wittenberg University, Springfield, OH, USA

ARTICLE INFO

Keywords:
Nuclear β decay
Geant4 simulations
CsI
NaI detectors
Bremsstrahlung radiation

ABSTRACT

The yield of photons produced by electrons slowing down in CsI and NaI was studied with four electromagnetic physics constructors included in the Geant4 toolkit. The subsequent absorption of photons in detector geometries used for measurements of the β spectrum shape was also studied with a focus on the determination of the absorption fraction. For electrons with energies in the range 0.5–4 MeV, the relative photon yields determined with the four Geant4 constructors differ at the level of 10^{-2} in amplitude and the relative absorption fractions differ at the level of 10^{-4} in amplitude. The differences among constructors enabled the estimation of the sensitivity to Geant4 simulations for the measurement of the β energy spectrum shape in ^{6}He decay using a calorimetric technique with ions implanted in the active volume of detectors. The size of the effect associated with photons escaping the detectors was quantified in terms of a slope which, on average, is respectively −5.4 %/MeV and −4.8 %/MeV for the CsI and NaI geometries. The corresponding relative uncertainties as determined from the spread of results obtained with the four Geant4 constructors are 0.0067 and 0.0058.

1. Introduction

Precision measurements of the Fierz interference term in nuclear and neutron decays offer high sensitivity to searches for exotic scalar and tensor couplings contributing to the weak interaction [1,2]. The most direct way to access the Fierz term is through measurements of the shape of the β-energy spectrum and the current challenge is to reach a sensitivity level below 10^{-3} [2]. Measurements of β-energy spectra have mostly been performed using either magnetic spectrometers [3,4] or particle detectors in configurations in which the suitable β emitter was located outside the active volume of a detector [5]. One of the most severe instrumental effects in the detection of β particles for precision measurements is their backscattering from the detector volumes, resulting in significant distortions of the measured spectra [5].

A common tool to describe the backscattering of electrons in matter is offered by the Geant4 toolkit [6]. The performance of Geant4 for the description of backscattering has recently been studied for semiconductor [7,8] and plastic scintillator detectors [9] used in nuclear decays. Measurements and quantitative analysis have also been carried out in the energy range of neutron decay [10,11]. The misidentification of the electron energy at those energies has motivated the development of backscatter-suppressed spectrometers [12] to reduce the impact of such undesirable effects. The results in Ref. [8] showed that, for semiconductor detectors, the relative intensities in the description of spectra can be reproduced within ±3% in amplitude over selected energy ranges. However, the same studies indicate possible limitations of Geant4 for precision measurements of the shape of β energy spectra. This is illustrated for instance by the presence of marked slopes in Fig. 17 of Ref. [8]. Systematic studies of the Geant4 simulation of electron backscattering, with focus in the low energy range, down to 0.1 keV, have observed a large variability in the performance of all models for the determination of the backscattering fraction [13].

A new calorimetric technique was recently proposed with the aim to eliminate the effect of electron backscattering for measurements of β-energy spectra [14]. In this technique, the suitable β emitter is implanted

* Corresponding author at: National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI, USA.
E-mail address: naviliat@nscl.msu.edu (O. Naviliat-Cuncic).

https://doi.org/10.1016/j.nima.2017.10.061
Received 24 August 2017; Received in revised form 17 October 2017; Accepted 19 October 2017
Available online 31 October 2017

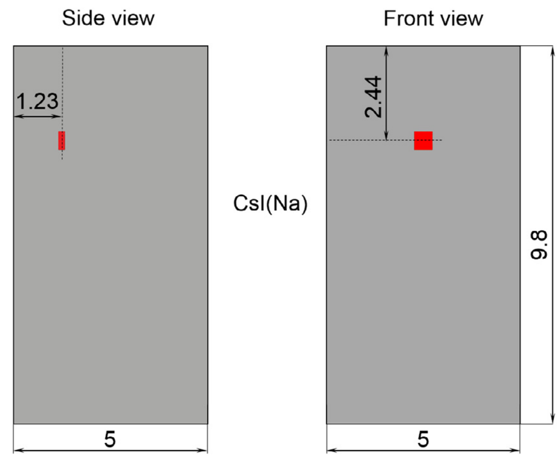

Fig. 1. (Color online) Geometry of the CsI(Na) detector (gray) and position of the electron source (red) used in the simulations. Dimensions are in cm.

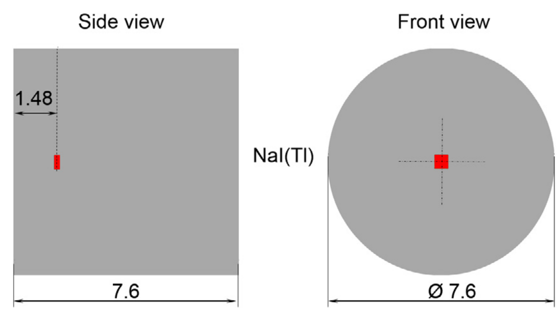

Fig. 2. (Color online) Geometry of the NaI(Tl) detector (gray) and position of the electron source (red) used in the simulations. Dimensions are in cm.

inside a detector and the spectrum is then measured during the decay. Because of the finite detector size, a fraction of the initial β-particle energy escapes the detector through photons, resulting in a distortion of the spectrum shape.

This paper reports on a study of four physics constructors included in Geant4 with the aim to test the variability in the description of photon production and absorption and to estimate the impact of such variability in the analysis of the spectrum shape in ^{6}He decay. The study focuses on the energy absorbed in CsI and NaI materials by electrons produced inside these materials with energies up to 4 MeV.

2. Source and detector geometries

The geometries of the source and detectors used in the simulations are shown in Figs. 1 and 2. They correspond to actual experimental conditions [14] but the description of their achievement is outside the scope of the present study. One detector is a rectangular cuboid 9.8×5×5 cm^3 CsI(Na) scintillator (Fig. 1) and the other is a cylindrical Ø7.6 × 7.6 cm^2 NaI(Tl) scintillator (Fig. 2). The geometry of the electron sources is described by a rectangular cuboid, with dimensions $4.6 \times 4.5 \times 1.5$ mm^3 in CsI(Na) and 4.6×4.5×1.7 mm^3 in NaI(Tl). The position of the center of the source in the CsI(Na) detector is 2.44 cm from the top and 1.23 cm deep from the front face. In the NaI(Tl) detector, the source is located on the cylindrical axis at a depth of 1.48 cm from the front face.

3. Geant4 constructors and conditions

Electrons lose energy in CsI and NaI by collision and bremsstrahlung radiation. Collisions include ionization and excitation processes which can give rise to secondary Auger electrons and X-rays. These processes are described in the Geant4 toolkit with various models. The present study used version 10.3.0 of Geant4.

Table 1
Physics lists and constructors of Geant4 used in the present study.

Physics constructors and lists	Denomination
`PhysListEmStandard`	Standard
`G4EmLivermorePhysics`	Livermore
`G4EmPenelopePhysics`	Penelope
`G4EmStandardPhysics_option4`	Option4

3.1. *Geant4 physics constructors*

The physics processes are organized in a number of *physics constructors* which implement "electromagnetic physics lists". Some constructors are adapted to low energy processes and the constructors can sometimes differ by their calculation efficiencies. To test the variability of the results, this study has considered the physics constructors and lists presented in Table 1.

The electromagnetic models included in the physics constructors are described in the Geant4 Physics Reference Manual [15]. In particular, the description of bremsstrahlung are based respectively on the models `G4SeltzerBergerModel`, `G4LivermoreBremsstrahlungModel` and `G4PenelopeBremss trahlung-Model` for the Standard (std), Livermore (liv) and Penelope (pen) constructors. The on-line documentation [16] describes Option4 (opt4) as using the most accurate standard and low-energy models. This constructor is not independent from the other three. The inspection of the source indicates that, for the electron energies considered in this work, it uses `G4SeltzerBergerModel` for bremsstrahlung. The Standard list is not specifically adapted for low energy processes but has been included here to compare the results with Option4. The actual list used here was taken from Ref. [17]. According to the Physics Reference Manual [15], the constructors optimized for low energies like Livermore and Penelope, use all common data libraries such as the Evaluated Electron Data Library.

3.2. *Geant4 geometry*

The geometries of the source and detectors described in Section 2 have been implemented in the Geant4 simulations. The selected absorber materials were CsI for the CsI(Na) detector and NaI for NaI(Tl). The primary particle source includes only electrons, uniformly distributed within the volume of the sources inside the detectors (Figs. 1 and 2) and emitted isotropically. Two types of energy distributions for the electrons have been studied: 1) a set of monoenergetic values in the range 0.5–4 MeV and 2) the continuous β spectrum associated with ^{6}He decay which extends up to 3.5 MeV.

An illustration of a simulation with the geometry implementation for the CsI material, with 10^3 events for 1 MeV electrons is shown in Fig. 3. The simulation was performed with the Standard constructor. The electrons (in red) remain inside the detector while some of the photons (in green) escape.

3.3. *Geant4 parameters*

All default values of parameters used in the physics lists have been adopted. The tracking of primary and secondary particles can be controlled via other parameters. The parameter that controls the creation of secondaries is the range cut (or Cut For Secondaries). The creation occurs if the particle is able to travel over a distance larger than this range in a given material. Otherwise the particle energy is absorbed locally. Unless stated otherwise in the text for specific conditions, the values of the range cuts were fixed to 5.0 μm in CsI and 5.7 μm in NaI for both electrons and photons. For the range factor parameter, F_R, and geometry factor parameter, F_G, [18], which are important for multiple scattering, the default values have been used (F_R = 0.02, F_G = 2.5 for Penelope, Livermore and Option4 and F_R = 0.04 for Standard).